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EXPERIMENTAL INVESTIGATIONS ON LVL SEISMIC RESISTANT WALL AND FRAME SUBASSEMBLIES

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SUMMARY

Based on the recent developments on alternative jointed ductile dry connections for concrete multi-storey buildings, the paper aims to extend and propose similar innovative seismic connections for laminated veneer lumber (LVL) timber buildings. The dry connections herein proposed are characterised by a sort of rocking occurring at the section interface of the structural elements when an earthquake occurs; unbonded post-tensioned techniques and dissipative devices respectively provide self-centring and dissipation capacities. The paper illustrates some experimental investigations of an extensive campaign, still undergoing at the University of Canterbury (Christchurch, NZ) are herein presented and critically discussed. In particular, results of cyclic quasi-static testing on exterior beam-column subassemblies and wall-to-foundation systems are herein presented; preliminary results of pseudo-dynamic testing on wall-to-foundation specimens are also illustrated. The research investigations confirmed the enhanced seismic performance of these systems/connections; three key aspects, as the no-damageability in the structural elements, typical "flag-shape" cyclic behaviour (with self-centring and dissipation capacity), negligible residual deformations, i.e. limited costs of repair, joined with low mass, flexibility of design and rapidity of construction LVL timber, all create the potential for an increased use in low-rise multi-storey buildings.

1. INTRODUCTION

In the last decade, construction developments in the seismic protection and refinements of performance-based seismic design/engineering (PBSE) philosophies highlight the importance of designing ductile structural systems to undergo inelastic cycles during earthquake events while sustaining their integrity, recognizing the economic disadvantages of elastic design of buildings to withstand earthquakes with no structural damage. This particularly applies to multi-storey buildings in moderate or high seismic regions.

The improvements of seismic design philosophies and innovative structural systems come out in parallel and are strictly related with an increased focus on limited damage objective, as observed in recent years.

As a consequence, the critical role of residual deformations, i.e. costs of repair after an earthquake event, currently defining the seismic performance of structures as an additional and complementary indicator of damage, has been recently emphasized in literature (MacRae and Kawashima, 1997), (Pampanin et al., 2002), (Christopoulos and Pampanin, 2004), (Mackie and Stojadinovic, 2004), while innovative jointed ductile dry connections for precast concrete have been developed by (Priestley 1991, 1996, Priestley et al., 1999).

The development of these alternative solutions for precast concrete buildings introduced innovative concepts in the seismic design of frame and shear wall systems: alternatively to the emulation of cast-in-place approach, pure precast elements are assembled through post-tensioning techniques, with the inelastic demand being

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accommodated within the connection itself (beam-to-column, column-to-foundation, wall-to-foundation critical interfaces). A particularly efficient solution was offered by the hybrid system/connection, developed within the U.S.-PRESSS Program (PREcast Seismic Structural System), coordinated by the University of California, San Diego, (Priestley, 1991, 1996), (Stanton et. al., 1997), (Priestley et al., 1999), where unbonded post-tensioning tendons/bars with self-centring properties are adequately combined with longitudinal mild steel or supplemental damping/dissipation devices, which can provide an appreciable energy dissipation (**Figure 1a**).

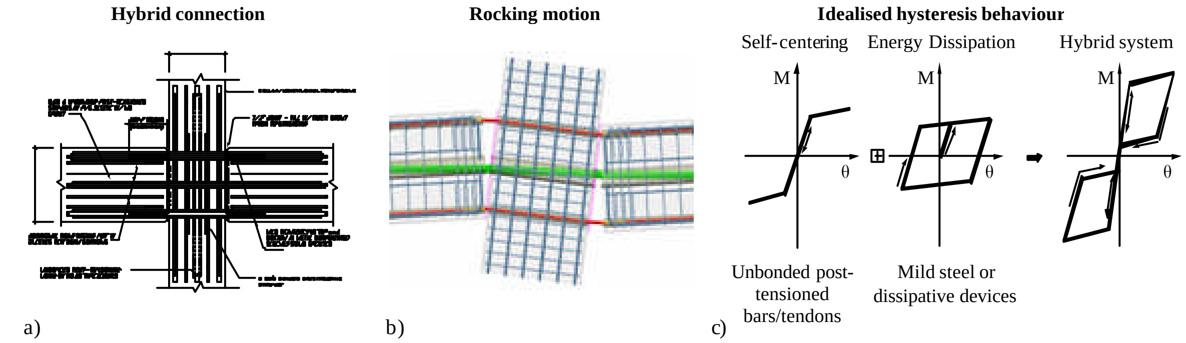


Figure 1: a) Hybrid connection (Priestley et al. 1999); b) rocking motion mechanism (Courtesy of Susy Nakaki); c) idealised flag-shape hysteresis behaviour (fib 2003)

Being the seismic inelastic demand accommodated within the connection itself, when a seismic event occurs, a sort of "controlled rocking motion", with a opening and closing of an existing gap, governs the behaviour of the hybrid system (**Figure 1b**); as a result, the combined self-centring and dissipation capacity characterise the connection by a peculiar "flag-shaped" hysteresis loop (**Figure 1c**).

These solutions, which are independent of the mechanical properties of the adopted structural material, i.e. concrete, steel (Christopoulos et al., 2002), timber, achieve adequate global ductile behaviour relying on the plastic deformation of the sacrificial internal and/or external dissipaters, designed according to capacity design principles in order to protect the whole system from undesired inelastic mechanisms in the structural elements.

The concept of hybrid systems/connections is proposed to be extended to laminated veneer lumber LVL solutions for multi-storey frame or shear wall buildings, where as a structural material, due to the higher homogeneity, LVL can be considered as a superior alternative to sawn timber or glulam. The performance of these innovative jointed ductile connections can be considered a superior alternative to the existing moment-resisting connections developed in literature for solid sawn timber, glue laminated timber (glulam), or LVL lateral load resisting wall or frame systems.

Depending on the connection typology, many alternative arrangements have been investigated, proposed and adopted ranging from mechanically fastened solutions with nailed, bolted or dowel connections to glued or epoxied steel rods. Significantly different forms of inelastic cyclic behaviour can occur, leading to different levels of ductility capacity and hence different overall structural performance. Typical pinching phenomena can be observed in the hysteresis behaviour of nailed or steel rods connections (**Figure 2a**) with a reduction of stiffness as well as of energy dissipation capacity, which leads to higher displacement demand (thus damage) than well designed steel or concrete structures. These hysteresis loops are similar to those achieved in structural walls with nailed plywood sheathing (Deam 1997).

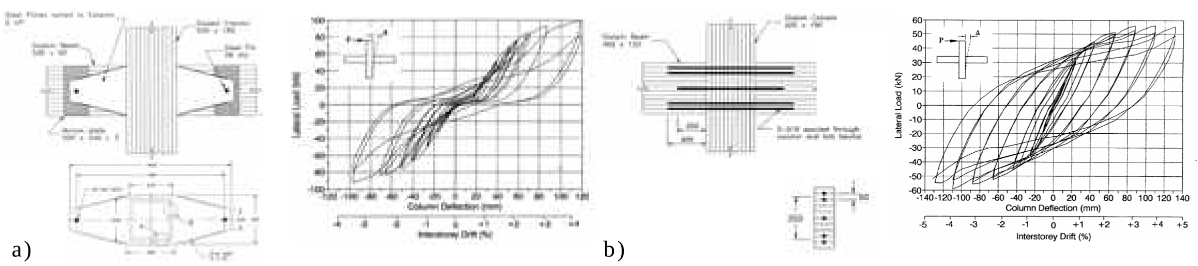


Figure 2: Layout and hysteresis loop for frame systems: a) multiple-nailed connection; b) epoxied rods glulam solution (Buchanan and Fairweather, 1993)

In an overview of seismic resisting solutions for multi-storey glulam timber buildings, Other solutions within steel epoxied connections with or without additional steel sacrificial brackets to accommodate the inelastic behaviour have been proposed by (Buchanan & Fairweather 1993). **Figure 1b** showed the satisfactory cyclic behaviour of the epoxied rods glulam solution, which can be assumed similar to the performance of a properly designed plastic hinge in reinforced concrete members. A stable dissipating hysteresis loop and limited stiffness degradation is outlined by the force-displacement curve, even if too excessive residual (permanent) displacement occurs during the test.

On the basis of the preliminary experimental tests carried out in (Palermo et al. 2005), additional experimental investigations are herein reported, focusing on the developments of different arrangements of hybrid connections for multi-storey laminated veneer lumber (LVL) timber buildings. Quasi static cyclic and pseudo-dynamic testing are carried out, considering typical beam-column and wall-to-foundation subassemblies. A series of different solutions, either post-tensioned only or hybrid solutions, with different types of dissipaters are presented and critically discussed.

2. QUASI-STATIC CYCLIC TESTS ON EXTERIOR BEAM-COLUMN SUBASSEMBLIES

This paper presents the results obtained from quasi static cyclic tests on exterior beam-column subassemblies. Two unbonded post-tensioned solutions (i.e. using unbonded post-tensioning only as reinforcement), with different level of initial post-tensioning, already presented in (Palermo et al. 2005) are briefly described, while more focus will be given to the four hybrid specimens (i.e. combining unbonded post-tensioning with additional non-prestressed reinforcement) with different dissipation devices.

2.1 Test set-up description

The adopted test set-up for quasi-static tests on beam-column joint subassemblies is shown in **Figure 3**. The beam is 1.5m long and the column is 2.0m long. The load was applied at the points of contra-flexure, typically assumed, to be at mid-span of the beam and at mid-height of the column. The beam contact section geometry of the four hybrid solutions is also illustrated in right part of **Figure 3**. The loading protocol is the same for all the solutions considered, comprising of a series of three cycles of inter-storey drift, applied at increasing levels through the horizontal hydraulic actuator; the testing protocol for acceptance criteria through tests on innovative jointed precast concrete frame systems proposed by ACI T1.1-01, ACI T1.1R-01 document (2001) have been adopted. The column axial load was kept constant during the experiments through the vertical hydraulic actuator (120 kN).

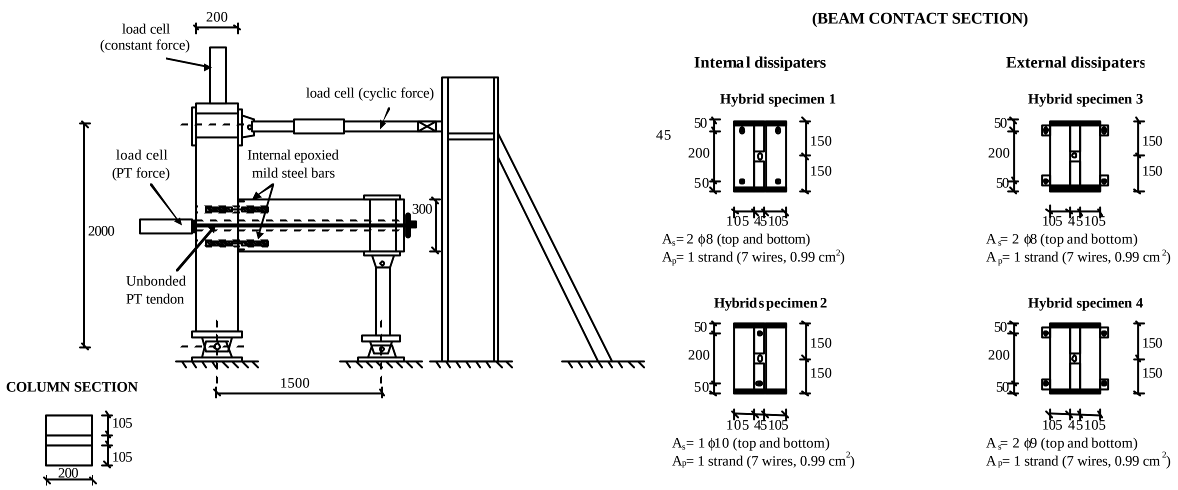


Figure 3: Test set-up and geometry details

Table 1: Material properties

Materials	Beam-column/wall-to- foundation specimens
(LVL Hy63/105, parallel to the grain): f_c, E_c	34 MPa, 13.2 GPa
(LVL Hy63/105, perpend. to the grain): f_p, E_p	12.0 MPa, 13.2 GPa
Mild steel bars, i.e. internal dissipaters: f_{sy}	340 MPa (yield)
7-wire pre-stressing strand (A_{pt}=99mm^2): f_{py}	1530 MPa (yield), 1870 MPa (0.2% proof stress)

The material properties shown in **Table 1**, which are based on specific material testing results given by Carter Holt Harvey (LVL manufacturing company), highlight the significantly different behaviour of LVL material in the directions parallel and perpendicular to the grain. A three times reduction in strength and increase in deformability has to be expected when loading perpendicular to the grain. The face of the column, which is in contact with the end of the beam, becomes the critical contact part to be considered during the design process.

2.2 Unbonded post-tensioned solution

The geometry of an exterior beam-column subassembly, shown in **Figure 3** is common the two unbonded post-tensioned solutions with different initial values of post-tensioning ($0.4f_{py}$ and $0.6f_{py}$, with f_{py} the yield stress of the post-tensioning steel, i.e. UPT1, UPT2), herein presented. The material properties of tendon are reported in **Table 1**.

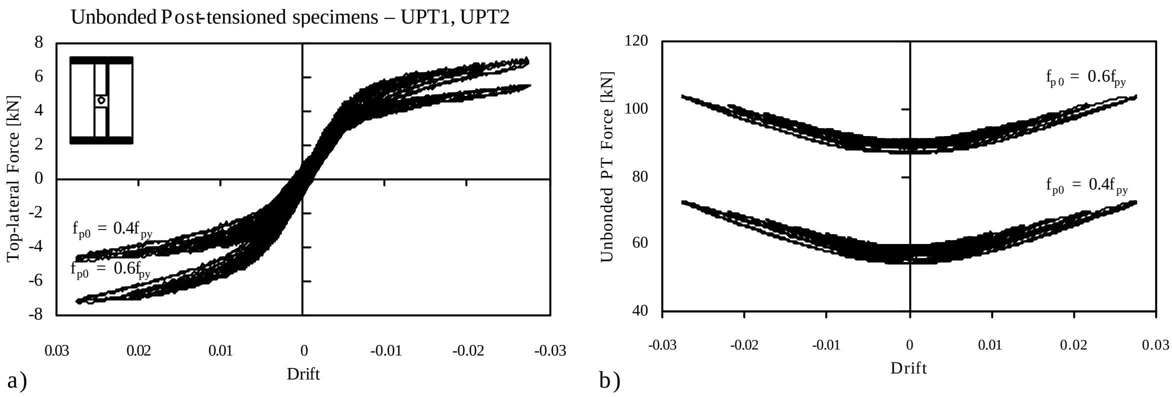


Figure 4: Internal and external dissipaters and construction

Figure 4a shows the recorded values of lateral force vs. inter-storey drift (ratio of top-displacement and column height), mainly characterised, as expected, by a pure non-linear elastic hysteresis with fully re-centring properties. The minor amount of hysteretic dissipation is given by the local non-linear behaviour of the LVL material at the column contact section, loaded in compression perpendicular to the grain. The hysteresis curve shows non linear behaviour with an equivalent "yielding", which is due to geometrical non-linearity, not related to material non-linearity, due to a sudden relocation of the neutral axis position. The reduced stiffness after the equivalent "yielding" corresponds to an increase in moment capacity primarily due to the elongation of the tendons as confirmed in **Figure 4b**. A similar increment of the initial post-tensioning force for the two solutions ($0.4f_{py}$ and $0.6f_{py}$), due to the gap opening, respectively reaching a maximum of 73.4 kN ($0.4f_{py}$) and 103.5 kN ($0.6f_{py}$) is achieved. Both the maxim tendon forces are far way from the yielding tendon force, i.e. 151,4 kN. The test was interrupted at 2.75% drift level only to preserve the column test specimen from possible compression crushing damage before modifying it for the hybrid solutions.

2.3 Hybrid solution

The same specimen which had been tested up to 2.75% drift in the pure unbonded post-tensioned condition have been successively for testing four different arrangements, consisting of two hybrid solutions with internal and external dissipaters.

Figure 5 (left side) shows the details of the internal energy dissipaters for the hybrid solutions (HY1, HY2). The first specimen HY1 uses two ϕ10 mm (grade 340, see **Table 1**) deformed bars, machined to a reduced diameter (ϕ8 mm) to create a fuse along an unbonded length of 50 mm, located at the top and bottom fibres, while the second specimen has one fully bonded ϕ10 mm (grade 340) deformed bar located at the top and bottom of the beam. After inserting the deformed bars through the beam and the column, epoxy is successively injected in order to guarantee proper bond. The unbonded length, for the specimen HY1 was specifically designed in order to limit the strain demand at the location of the gap opening and prevent a premature failure of the energy dissipators which could compromise the overall performance of the connection. The hybrid solutions with external dissipators, briefly named HY3, HY4 are characterised by the adoption of four external deformed bars (two for each side of the beam) respectively consisting of 8 and 7mm bars encased in steel tubes with epoxy to prevent buckling (**Figure 5**, right side). The threaded extremities of the dissipaters allow to easily fix and remove

the devices from the steel case, opportunely fixed through prestressed rods to the LVL beam and column. The effective length of the dissipaters for both the specimens was 50 mm.
Different variations of initial prestressing have been considered for the four hybrid specimens: $0.8f_{py}$ for the specimens HY1, HY2, i.e. internal dissipaters and $0.6f_{py}$ for the specimens HY3, HY4, i.e. external dissipaters.

INTERNAL DISSIPATERS:
epoxied mild steel bars with unbonded length

EXTERNAL DISSIPATERS:
mild steel rods with epoxied encased steel tubes

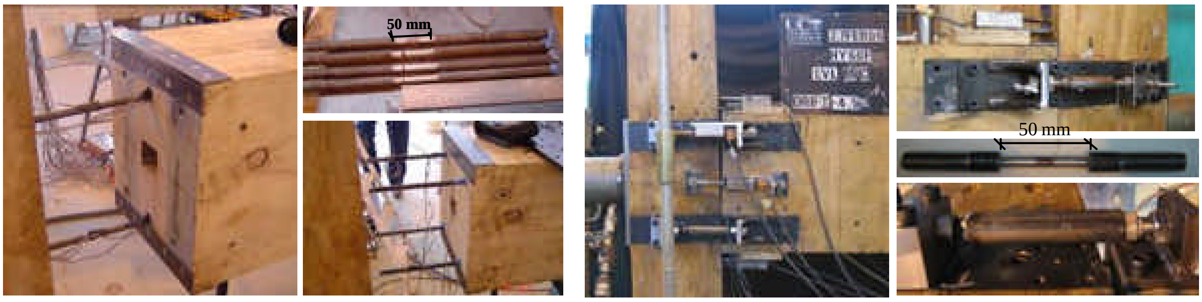
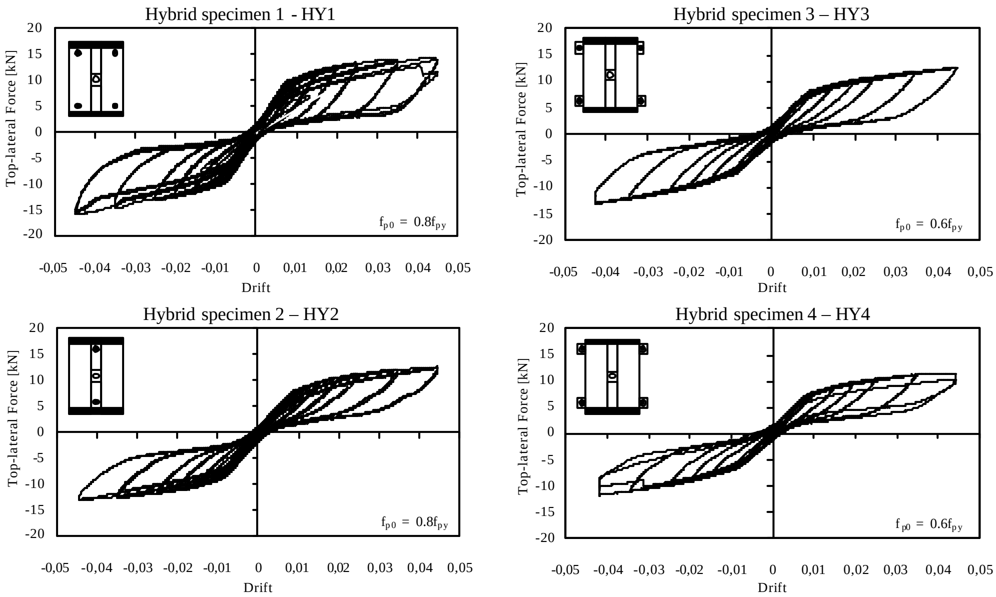


Figure 5: Internal and external dissipaters and construction

The dissipaters' sizes (diameter and unbonded and/or effective length) come out from a comprehensive design calculation, which guarantees the desired ratio, λ (Palermo et al. 2005, NZS 3101:2006), between the self-centring and the energy-dissipating moment contributions. As a result, very stable flag-shape hysteresis behaviours were obtained, as expected, with re-centring capacity (negligible static residual displacements) and adequate energy dissipation capacity, as shown in **Figure 6a** (internal dissipaters), **Figure 6b** (external dissipaters), where the force-displacement curves are represented.



a) b)

Figure 6: Force vs. drift: a) hybrid solution with internal dissipaters; b) hybrid solution with external dissipaters

In these cases, the equivalent yielding point corresponds to actual yielding of the dissipation devices, approximately observed at 0.8% inter-storey drift. During repeated cycles beyond the yielding drift level, some onset of stiffness degradation was observed for the specimens HY1, HY2, probably due to bond deterioration between the deformed mild steel bars and LVL through the epoxy. No stiffness degradation have been observed for the solutions with external dissipaters (HY3, HY4). The level of tendon force due to initial prestressing plus elongation induced by the opening of the gap has been controlled with a proper design in order to guarantee an elastic contribution (full re-centring) without losses of prestressing or undesired premature rupture of dissipators, up to the target level of drift. The different section arrangements of the hybrid specimens, i.e. different initial

post-tensioning, different dissipaters' size and typology, confirm the high flexibility of design of the hybrid systems, where similar global responses have been obtained by the four abovementioned specimens.
Figure 7 shows no visible damage in the beam or the column occurring, when 4.5% drift levels are reached during the testing. A part, from the HY2, in the other cases the tests was interrupted because of the failure of one dissipater under repeated cycles after buckling in the unbonded and/or effective length.

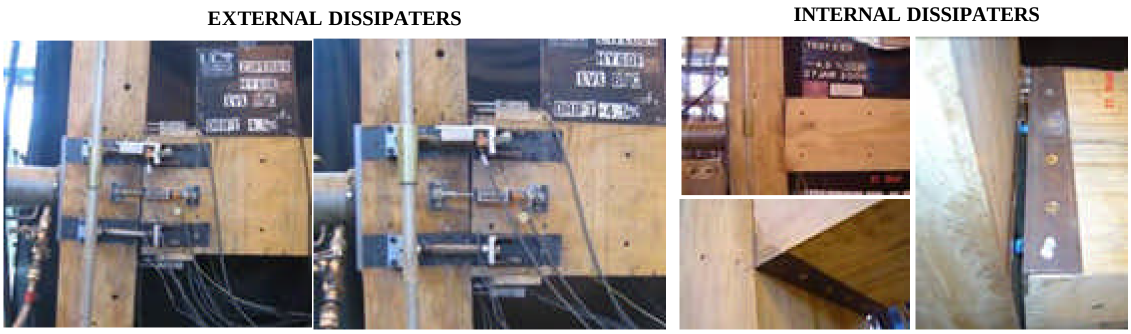


Figure 7: Hybrid solutions with internal and external dissipaters: performance at 4.5% drift level

3. EXPERIMENTAL TESTS ON WALL-TO-FOUNDATION SPECIMENS

3.1 Quasi-static cyclic testing on hybrid solutions

As part of the investigation of frame subassemblies, a series of quasi-static cyclic tests on cantilever walls connected to the foundation have been carried out. For sake of brevity, only three hybrid solutions are herein presented: two with internal dissipaters and one with external dissipaters.

3.1.1 Test set-up description

As shown in **Figure 8**, the specimen consisted of a rectangular LVL wall (1.72 m high) connected to a concrete foundation with a proper cavity, necessary to allocate and fix the two unbonded post-tensioned tendons. The cantilever wall was loaded at the expected point of contra-flexure within a frame systems, thus mid-height of the inter-storey height, imposing the displacement loading protocol adopted for the above mentioned beam-to-column subassemblies. No additional axial load was applied, and the initial post-tensioning of the two tendons passing through the foundation (**Figure 8**) includes the axial force due to the gravity load. The LVL properties (Hy63) of the wall specimen are reported in **Table 1**.

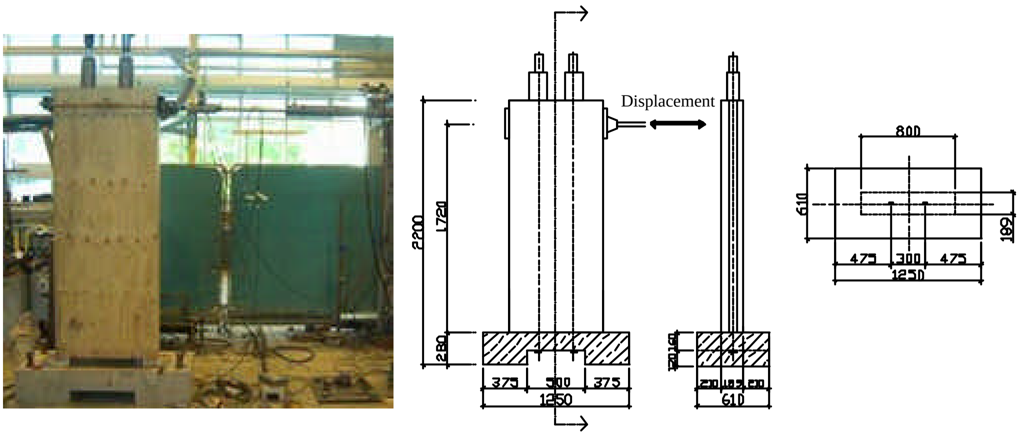


Figure 8: Test set-up and geometry details

Figure 9 shows the different typologies of dissipaters developed and still under investigation; The internal dissipaters herein presented, respectively characterising the hybrid solution 1 (HY1) and 2 (HY2) are ϕ16 mm (grade 340, see **Table 1**) deformed bars, machined to a reduced diameter (ϕ12 mm for HY1, ϕ10 mm for HY2) creating a fuse along an unbonded length of 200 mm. These dissipaters are threaded at their bottom extremity and fixed to concrete foundation before placing the wall specimen; the top extremity is corrugated for a certain length necessary to provide the bond between the dissipater and LVL by injection of epoxy. The unbonded length of 200 mm, for the two specimens HY1, HY2 comes out from a proper design with the aim to limit the strain demand at the location of the gap opening. Two types of external dissipaters are shown in **Figure 9**, but only the hybrid solution with external LVL-steel dissipaters (HY3) is herein illustrated. The LVL-steel dissipater is composed by LVL block, 63mm thick, fixed to pre-tensioned rods to the wall specimen, with inserted ϕ6 mm epoxied deformed bars. The bottom extremity of the deformed bar is fixed to the concrete foundation. The steel dissipaters, not herein adopted are very similar to the ones, adopted for the exterior beam-column subassemblies, i.e. bars encased in steel tubes fixed to external steel cases.

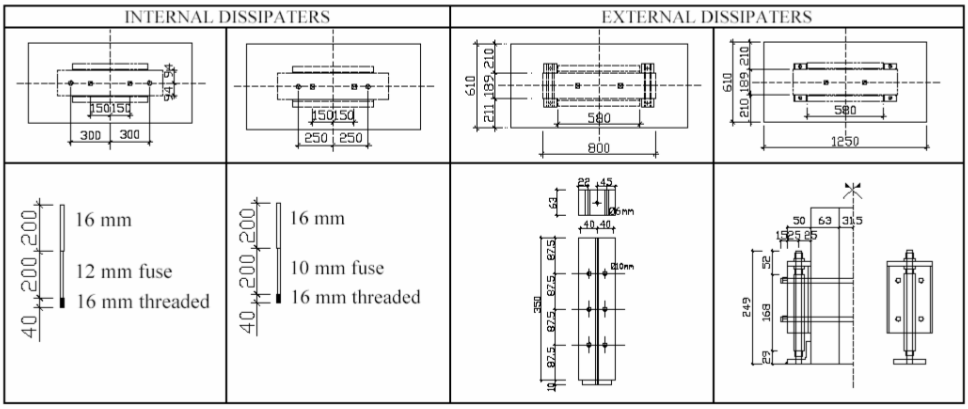


Figure 9: Details of internal and external dissipaters

3.1.2 Hybrid solution

Different variations of initial prestressing have been considered for the three hybrid specimens: $0.3f_{py}$ for the specimen HY1 and $0.36f_{py}$ for the specimens HY2 (internal dissipaters), HY3 (external dissipaters). The lower level of initial post-tensioning for the hybrid wall specimens (0,36 and $0,3f_{py}$) compared to the exterior beam-column subassembly (0,6 and $0,8f_{py}$), is strictly related to height of the rocking wall section, where for a not significant gap opening a marked elongation of the tendons occurs, as illustrated in **Figure 10a** where the forces of the two tendons vs. drift level are represented. **Figures 10b, 10c** shows the global lateral force vs. drift of the two hybrid solutions with internal dissipaters.

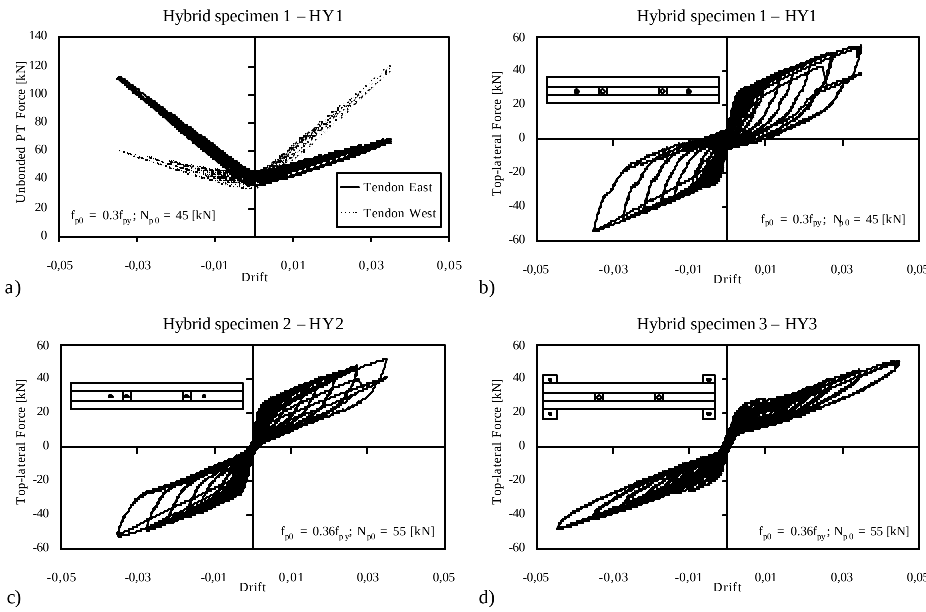


Figure 10: Hybrid solution; a) Unbonded PT force vs. drift (HY1); b) lateral force vs. drift (HY1); c) lateral force vs. drift (HY2); d) lateral force vs. drift (HY3);

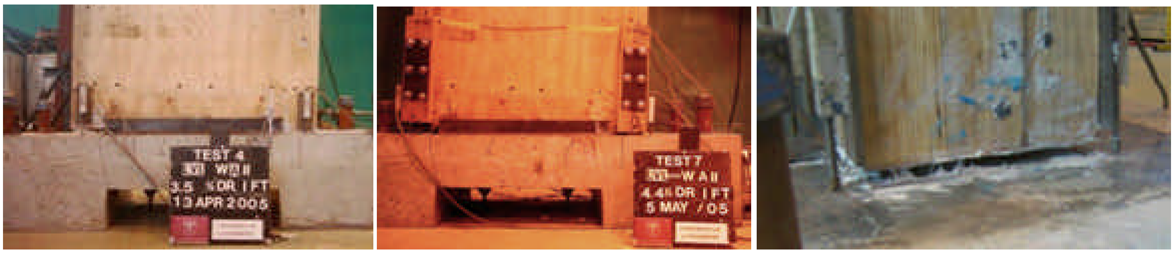


Figure 11: Performances of hybrid solutions with internal and external dissipaters at different drift levels

In these cases, the equivalent yielding point corresponds to actual yielding of the dissipation devices, approximately observed at 0.4% drift level. The HY1 specimen is characterised by a greater dissipation capacity compared to the HY2 specimen despite of not enough self-centring properties. For both the specimens some onset of stiffness degradation, at medium-high drift levels can be observed especially during the loading part, due to bond deterioration between the dissipaters and the LVL specimen.

Similar considerations can be made for the hybrid solutions with external dissipaters, where a high self-centring capacity of the specimen is highlighted despite of a limited amount of dissipation capacity. Moreover, considering the more emphasised stiffness degradation during repeated cycles, it seems that the external LVL-steel dissipaters did not work properly due to excessive bond degradation, given by a non correct injection of the epoxy.

The pronounced elongations of the two tendons globally affect the cyclic behaviour of the connection, where the second post-yielding stiffness brings to a 100% increment of the yield force/moment capacity. **Figure 11** shows no visible damage in the wall specimen occurring at 3.5% drift levels (HY1, HY2) and 4.4 drift level (HY3) are reached during the testing. For specimens HY1, HY2 the test was interrupted because of the failure of one dissipater under repeated cycles after buckling in the unbonded length.

3.2 Pseudo-dynamic cyclic testing on pure unbonded post-tensioned solutions

A series of pseudo-dynamic tests was carried out to simulate slow motion (thus without strain rate effects) dynamic response of a structural system subjected to an earthquake input ground motion, on cantilever wall-to-foundation connections in unbonded post-tensioned-only configurations. The same test set-up, used for the quasi-static cyclic tests is herein adopted. The effects of various levels of initial post-tensioning (0.2, 0.3 and 0.4 f_{py}) on the dynamic response were investigated and provided valuable complementary information to that obtained from the quasi-static tests, not herein presented. The wall-to-foundation specimen is 2/3 scaled, hence, assuming a constant acceleration, a 2/3 scaling factor has to be applied to the time abscissa of the accelerogram adopted, i.e. Cape Mendocino seismic event record (**Table 2**).

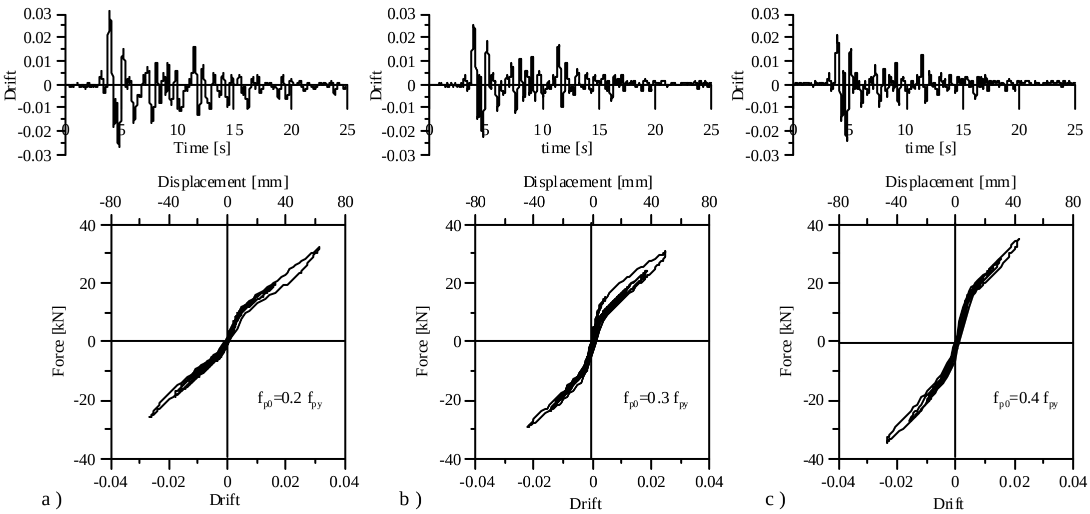


Figure 12: Unbonded PT solutions – drift vs. time, force vs. drift: a) $f_{p0}=0.2f_{py}$; b) $f_{p0}=0.3f_{py}$; c) $f_{p0}=0.4f_{py}$

As part of the required information to solve the equation of motion of the SDOF system within the pseudo-dynamic algorithm, an equivalent mass of 74.075 kN s^2/m (0,296 scaled down respect to the real value) was assumed. It corresponds to the expected gravity load (dead load plus a portion of the live load, i.e. 5.0 kN/m^2) for the tributary area (5m x 10m) of a wall within a one storey timber building. An equivalent viscous damping of 5% was assumed.

Figure 12 shows the responses of the three solutions with different level of post-tensioning under a recorded Cape Mendocino accelerogram (**Table 2**) in terms of a drift time-history and a force-displacement envelope.

Table 2: Characteristics of the Cape Mendocino earthquake record adopted

Year	Mw	Station	$R_{closest}$ [km]	Soil Type (NEHRP)	Duration [s]	Scaling Factor	Scaled PGA (g)
1992	7.1	Fortuna Fortuna Blvd	23.6	C	44.0	3.8	0.441

The behaviour is very similar to the unbonded post tensioned beam-to-column solutions presented in paragraph 2.2. In fact, increasing the initial post-tensioning level corresponds to an increase of the "yielding force" level. Moreover, ranging from an initial post-tensioning of $0.4f_{py}$ to $0.2f_{py}$ a reduction of 30% can be reached in terms of maximum drift demand.
Considering the force-displacements curves there is negligible hysteretic dissipation due to the friction between the longitudinal steel channel, placed to prevent transversal movements of the specimen, and the LVL specimens.

4. CONCLUSIONS

The experimental results of cyclic quasi-static and pseudo-dynamic tests on the herein presented wall-to-foundation and beam-column subassemblies confirmed the enhanced performance of the hybrid jointed ductile connections.
The hybrid solutions allow to have a great flexibility in the seismic design of the connections, as confirmed by the different arrangements investigated, i.e. different types of dissipaters combined with different initial post-tensioning of the tendons. Three important aspects are guaranteed: high levels of ductility, negligible residual deformations and no-damage of the structural elements.
Moreover, being the dissipaters the only sacrificial parts of the connection system, improved reparability is provided comparing to traditional solutions in timber construction (e.g. nailed or steel dowel connections). Both internal and external dissipaters have given encouraging performances for the hybrid solutions adopted, but the hybrid solutions with external dissipaters may be preferred to those with internal epoxied bars due to the much easier replacement after a seismic event, even if the construction technology for external dissipaters is more expensive.
The flexibility of design and speed of construction of the LVL components, combined with the enhanced seismic performance of the hybrid solutions, creates unique potential for future development and increased use of this type of construction in low-rise multi-storey buildings in the world wide.
Further experimental investigations for the development of LVL hybrid solutions and feasibility studies are currently ongoing and will be extended to cover alternative lateral load resisting systems considering different arrangements, such as tendon profiles and new source of dissipations.

5. ACKNOWLEDGEMENTS

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